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Particle manipulation via integration of electroosmotic flow of power-law fluids with standing surface acoustic waves (SSAW)

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HIGHLIGHTS

- Integration of EO flow with SSAW based particle manipulation technique.
- Mathematical model for EO flow of non-Newtonian fluids in SSAW-based device.
- Investigation of effect of fluid rheology & operational parameters on particle motion.

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ABSTRACT

Standing surface acoustic wave (SSAW) based microfluidic devices have shown great promise toward fluid and particle manipulation applications in medicine, chemistry, and biotechnology. In this article, we present an analytical model for investigating continuous manipulation of particles (both synthetic and biological) within electroosmotic flow of non-Newtonian bio-fluids in a microfluidic channel under the influence of standing surface acoustic waves (SSAW). The particles are injected along the center of channel into the electroosmotically driven flow of power-law fluids, wherein their transport through the SSAW region is dictated by the hydrodynamic, electrophoretic, and acoustic forces. We first present a mathematical model to analyze the characteristics of electroosmotic flow of non-Newtonian power-law fluids in a hydrophobic slit microchannel. Next, we investigate the trajectories of particles in the flow field due to the combined effect of electroosmotic, electrophoretic, and acoustophoretic forcing mechanisms. The effect of key parameters such as particle size, their physical properties, input power, flow rate, and flow behavior index on the particle trajectories is examined while including the effect of the channel walls. The presented model delineates the methodologies of improving SSAW-based particle separation technology by considering the fluid rheology as well as the surface properties of the channel walls. Therefore, we believe that this model can serve as an efficient tool for device design and quick optimizations to explore novel applications concerning the integration of electroosmotic flows with acoustofluidic technologies.

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1. Introduction

Lab-on-a-chip microfluidic systems have received increased attention over the last few decades owing to their potential for medical and biotechnological applications [1,2]. One of the essential requirements for the success of such devices is the capability to precisely handle and manipulate small volume of fluids and particles/cells. While the small size of lab-on-a-chip systems offers inherent advantages in terms of low-cost, low sample volume requirement, easy automation etc., the physics at microscale makes fluid and particle manipulation non-trivial. For instance, rapid fluid mixing at microscales is non-trivial since it is dominated by the slow diffusion due to the laminar nature of the microfluidic flows [3]. Furthermore, the pressure difference required for pumping a fluid through a microchannel scales inversely with the fourth power of the microchannel radius, and thus increasing large pressure head is required to pump fluids through small microchannels. To overcome such challenges and achieve precise fluid and particle manipulation capabilities for lab-on-a-chip applications, researchers have integrated various physical processes onto a single chip such as electrostatics [4], magnetohydrodynamic [5–7], electroosmotic [8,9], acoustics [2,10–14] among others.

For particle manipulation applications, a number of techniques for continuous manipulation of biological cells and particles have been developed based on their intrinsic physical properties (e.g., size, shape, density, compressibility, polarizability) in microfluidic devices, as reviewed in Refs. [15–19]. Each of these available methods is associated with its own characteristic advantages and disadvantages. However, acoustic based microfluidic techniques have become increasingly popular because of their biocompatibility, label-free nature, compact size, and easy integration with other microfluidic units [20,21]. Nonetheless, one of the significant limitations of current acoustofluidic technologies is the possibility of fluid degradation associated with bio-fluid samples owing to their sensitivity to shear stress stemming from the parabolic flow profiles in these systems. In this article, we explore the possibility of overcoming this limitation by integrating acoustofluidic systems with electroosmotically driven flows that are characterized by plug-like velocity profiles.

Electroosmotic (EO) flow is the motion of liquid induced by an applied electric field across the channel and due to the presence of electrical double layer (EDL) at the channel wall [22]. The growing importance of the electroosmotic driven flows in microfluidics stems from their inherent benefits, such as plug-like velocity profile and negligible axial dispersion, absence of moving parts, no noise, easy fabrication, high reliability, and better flow control. While a number of analytical/numerical studies [23–31] have been reported for electroosmotic flows, the possibility of integration of such flows with acoustofluidic particle manipulation has received little attention. Such investigations are further complicated by the fact that a number of biomedical applications deal with a wide variety of biological and chemical fluids with complex rheological behavior that can be generally categorized as non-Newtonian fluids [32,33].

In this work, we present an analytical model to describe acoustic manipulation of particles/cells in an electroosmotically driven flow of non-Newtonian bio-fluids in a SSAW-based microfluidic device. We first provide detailed analytical solution for electroosmotic flow of non-Newtonian power-law fluids through a microchannel by taking into consideration the possibility of hydrophobic nature of the microchannel surface. This flow field is subsequently employed to investigate particle manipulation in a microfluidic channel by using SSAW. Further, by considering the interplay of acoustic, electrophoretic, and hydrodynamic forces, we obtain the particle velocity profiles through the non-dimensional equations of motion for particles in non-Newtonian bio-fluids. Lastly, we investigate the effect of key parameters such as particle size, their physical properties, input power, flow rate, and flow behavior index on particle trajectories while including the wall effect. We believe that the analytical model presented here will be useful for both the device design and optimization as well as to explore novel applications concerning the integration of electroosmotic flows with acoustofluidic technologies.

2. Description and mathematical formulation

Fig. 1 shows a schematic of the model device consisting of a microfluidic channel bonded onto a piezoelectric substrate in between a pair of identical interdigital transducers (IDTs).

A slit microchannel is filled with a liquid. The channel wall is assumed to be charged and the non-Newtonian liquid solution is modeled as a power-law fluid. An external electric field is imposed along the channel axis to create an electroosmotic flow (see Fig. 1). Particles are injected into microchannel via an inlet at center. In the absence of any acoustic actuation, the particles are expected to move along the center of channel due to laminar nature of the microfluidic flow.

However, upon actuating the IDTs via an electric signal, the two IDTs generate counter-propagating surface acoustic waves that interfere together to create a SSAW field. When a particle enters the SSAW active region, the acoustic radiation force deflects the particles trajectory toward the pressure node (or anti-node, depending on the fluid and particle properties), as illustrated in Fig. 1.

2.1. Constitutive model for the fluid

In the present work, the rheology of biofluid under investigation is described by the power-law fluid model. A power-law fluid is a type of generalized Newtonian fluid whose effective viscosity μ is given by

$$\mu = m\left|\frac{\partial u^*}{\partial y^*}\right|^{n-1} = m\left(-\frac{\partial u^*}{\partial y^*}\right)^{n-1}. \tag{1}$$